超高面密度垂直磁気記録方式の設計法の研究

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論文内容要旨

Chapter 1 Introduction

In order to realize the high potential of perpendicular magnetic recording, continuous experimental and theoretical analysis has been carried out to obtain the optimum head and media design. With the development of the computer, computer simulations have become indispensable to the theoretical analysis of recording mechanisms.

In 1967, the self-consistent magnetization calculation method was proposed [1]. This self-consistent magnetization calculation method brought about a new idea in 1974 that a circular magnetization mode would be formed in thick magnetic tape at short recorded wavelengths in longitudinal magnetic recording, which meant that a strong demagnetizing field was acting inside the tape. This could be considered as one of the discoveries that guided the beginning of perpendicular magnetic recording. The method opened a new path in the later computer simulation of magnetic recording.

In 1989, a 2-D finite element method (FEM) simulation program was developed by Tagawa [2]. In this program a vector magnetization of magnetic particles was introduced into calculations of magnetization distributions in recording media. The magnetic particles were assumed to reverse according to the curling model. The head-to-medium magnetic interactions could be taken into account. Because this program was 2-dimensional, only phenomena along the track center could be analyzed.

On the other hand, in 1988, Zhu and Bertram introduced the LLG equation approach to computer simulations of magnetic recording [3]. Based on this method, media noise, thermal stability and the effect of exchange coupling, can accurately be considered to explain experimental phenomena and aid in the design of media properties. However, nowadays, the complicated main pole tip, the overall head volume and the interactions between the head and medium are difficult for LLG equation method to deal with.

In order to increase the head field strength and improve the head field gradient, a narrow-track single pole head (SPT) with side shields, a tapered main pole and a tapered return path for 1 Tb/in^2 was proposed [4]. Since this analysis was based on the 3-D FEM, complicated pole structures and the overall volume of head could easily be dealt with. However, investigation of the head field strength and head field gradient alone is insufficient with regard to the effect of the head on recording resolution. Moreover, with the reduction of track width of the write head, 3-dimensional investigations of the head, head-medium spacing and media properties on the magnetization mechanism are indispensable. Furthermore, it is important to consider the head-medium interaction in the simulation of perpendicular magnetic recording. In this work, a new 3-D magnetic recording simulator was developed, by using this new simulator the effect of head and media properties on recording resolution was investigated, the design point for an extremely high areal density perpendicular magnetic recording system was proposed.

Chapter 2 Three dimensional Magnetic Recording Simulator

JMAG-Studio, which is based on 3D FEM, is a useful software for the analysis of head field distribution and head field gradient [5]. In this software, soft magnetic materials such as the main pole, underlayer and side shields were modeled by the saturation flux density and permeability parameters. Zero anisotropy was assumed. In the original program the hysteresis of the medium could not be considered.

In the media magnetization calculation, the magnetic particles of Co-Cr film were assumed to switch according to the Curling model. The Curling model could give a reasonable explanation of the large difference of the coercivity and anisotropy field of Co-Cr film. The anisotropy field and easy axes of magnetic particles were assumed to obey a normal distribution and the medium magnetization was calculated from probability distributions. User subroutines of JAMG-Studio were used to perform the magnetization calculation. Hsusr1.f was used to create the Curling model data array, magusr.f for the magnetization calculation and hsusr3.f for the media movement. In general, the Newton-Raphson method was used in the FEM calculation. As unique values of dM/dH could not be obtained from the media magnetization calculation, the successive iteration method was employed to obtain the converged solution. The calculated media magnetization was fed back into the FEM model after each iteration. Therefore, the demagnetization effect in the recording process and interactions between the head and media could be taken into account.

After each step of the calculation, the static magnetization state of medium was obtained and could be memorized by the anisotropy field probability distribution of the particles in each mesh. The head movement was performed by shifting the calculated magnetization and probability distributions of the previous step into the adjacent mesh of the medium. A regular medium mesh was necessary to realize this method.

In conclusion, a highly accurate 3-dimensional magnetic simulator was successfully developed in chapter 2.

Chapter 3 Head field distribution and field gradient of single pole head

In perpendicular magnetic recording, the single pole head, or SPT head, is one of the key devices. In this chapter, the head field distribution of single pole heads was investigated in detail, considering such issues as the effect of decreasing spacing and the thickness of recording layer, tapered main pole structure and the trailing side front yoke structure. The results could be summarized as follows.

(1) For the increase of head field, the decrease of spacing is more effective than that of the recording layer thickness due to the smaller magnetic reluctance.

(2) A tapered pole structure can provide a extremely high field strength, even larger than the saturation magnetization of main pole material, but the field gradient dHy/dx in low field strength region is to

some extent deteriorated, Therefore, corresponding the coercive force of the medium, there is an optimum throat height.

(3) By fabricating a trailing side return yoke in cusp SPT head, the recording resolution was improved. This structure is investigated in detail by calculation [6], with throat height of 50 nm and gap of 30 nm, the field gradient dHy/dx can be improved up to 280 Oe/nm in a large field strength area. Throat height is the most important parameter because the field strength Hy and field gradient dHy/dx can both improve with lower throat height. While the gap length and the saturate flux density of the trailing side return yoke are trade-off parameters. By the calculation, the minimum of the overall height and the thickness of the return yoke were decided.

Chapter 4 Effect of media magnetic properties on recording resolution

In chapter 3, methods to increase the head field strength and improve the head field gradient of the SPT head were investigated. Media properties, such as saturation magnetization, coercivity, and hysteresis loop slope etc., can also greatly affect the recording resolution. The width of isolated magnetization transition is an important parameter to indicate the recording resolution. In this chapter, at first, using 2 dimensional simulator 'SMART' [2], the effect of media magnetic properties on recording resolution, the transition width πa in down-track direction, was investigated.

Two kinds of head were used to calculate the magnetization transition [7], one was regular SPT head, another is trailing side return yoke SPT head. It was shown that the trailing side return yoke SPT head gives a larger head field gradient than the regular SPT head over a wide range of fields. The transition parameter was investigated for media with coercivities from 3 kOe to 9 kOe. It was discovered that the transitions in media with larger coercivity were sharper, and that the transition parameter was much smaller when using a return yoke SPT head than when using a regular SPT head. The recording resolution can be improved with the return yoke SPT head for a large range of media.

In the latter part, using the newly developed 3 dimensional simulator, the effect of magnetic spacing, side-shielded head structure, and exchange coupling of media, which were all considered to be factors that could influence the track width, were described.

Isolated magnetization transitions for four cases were calculated and compared [8]. Case 1 used the regular SPT head and set the spacing as 10 nm. Case 1 used the regular SPT head and decreased the spacing by 5 nm. Case 3 used the side-shielded SPT head in cross-track direction, and set the spacing as 10 nm. Case 4 used the regular SPT head, and considered the media exchange coupling by mean field coefficient of 0.3. To express the transition width, T_{50}, was defined as the distance between the 50% values of positive and negative magnetization. T_{50} was 19.1 nm, 15.8 nm, 18.8 nm, 13.6 nm for cases 1 to 4, respectively. In case 1 to 3, case 2 had the sharpest transition among the media without exchange coupling due to the large head field gradient and strong head media interaction. The sharpness of the transitions for cases 1 and 3 was almost the same due to the similar head field distribution in the down-track direction. When the mean field coefficient was introduced into the calculation, the residual magnetization increased because of the larger squareness ratio of the hysteresis loop. The transition of case 4 was even sharper than that of case 2.

In cross-track direction, the recorded track widths, defined as the distance between the points where the magnetization was 50% of the value at the track center, were 166.4 nm for case 1, 159.6 nm for case2, 162.2 nm for case3 and 176.2 nm for case 4. The track width of case 3, with the side-shielded head structure, was even larger than the track recorded with a 5 nm spacing (case 2), demonstrating the importance of head–medium spacing in double-layered perpendicular media. Although the track width increased in case 4 when exchange coupling was introduced into the media, the sharpness of the track edge was still higher than case 1.

In conclusion, decreasing the head-medium spacing improved the recording resolution in both the down-track and cross-track directions. A side-shielded head structure was also an effective way to decrease the track width. Discounting problems with media noise, using strongly exchange coupled media also improved the recording resolution.

Chapter 5 Consideration of GMR head reading resolution

In the previous chapters, recording process were simulated, in chapter 5, the effect of reproducing process on high density was investigated. Compared with the traditional inductive head, the GMR head, which takes advantage of the magneto-resistance effect, has a higher read resolution. After the introduction of MR heads to perpendicular magnetic recording in 1990, the rate of growth of areal density jumped dramatically to an annual rate of 60%. In this chapter, the reading resolution of GMR head was investigated. The parameters were the shield gap length and MR element track width.

Using 2D analytical expressions of the GMR head sensitivity function, the dependence of the sensitivity function on the shield gap length was investigated. It was shown that the sensitivity function is determined by the shield gap length, and is independent of the thickness of the MR element. The sensitivity function obtained by the analytical expression agreed well with that obtained by 2D FEM. By programming the ideal magnetization into the meshes of recording layer, the output could also be obtained by the FEM model. Using the model, the reproducing phenomena of GMR heads with different shield gap lengths were explained.

The dependence of GMR head reading resolution on the track width was investigated for both perpendicular and longitudinal recording, using 3D FEM [9]. With narrower track width, the sensitivity function in track center became narrower for perpendicular mode and sharper for longitudinal mode. The deterioration was obvious in track edge than that in track center. However, due to the small strength in the track edge, the ratio occupied by the sensitivity function in track edge in the overall output was small. As a result, it was shown that, although narrower track width heads have a higher resolution along the track center, the output of GMR head hardly changes. Therefore, resolution reduction due to the decrease of track width is not a concern.

Chapter 6 Conditions for achieving high areal densities with perpendicular magnetic recording

In terms of recording resolution, the effects of anisotropy field dispersions, easy axes dispersions, mean-field coefficient, media saturation magnetization and spacing were investigated. Comparing with other factors, the decrease of the dispersion of anisotropy field and the decrease of magnetic spacing had significant decrease in the transition width and track width. Therefore, control of these two factors is an indispensable condition for achieving high density recording in the single pole head and double layer perpendicular magnetic recording system.

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論文審査の結果の要旨

情報蓄積技術は、ここ数年来、年率100%の驚異的なペースで大容量化・高速化を実現し高度情報化社会実現の牽引車となってきたが、最近になって技術的な壁に直面し伸び率が鈍化しており、垂直磁気記録方式の導入が待望されている。超高面密度垂直磁気記録装置の作製には磁気ヘッド・媒体間の磁気的相互作用を考慮した精密な設計手法の開発が必須となっていた。著者は、この磁気的相互作用を取り込んだ三次元記録シミュレータを開発し、これを用いて具体的なヘッド・媒体設計パラメータを提案し、 平方インチ当たり200ギガビットの超高面密度垂直磁気記録方式のハードディスク装置実現に貢献している。本論文はその成果をまとめたものであり、全編7章からなる。

第1章は序論である。

第2章では、三次元有限要素法による電磁界解析法と媒体内部磁化のセルフコンシステント磁化計算法とを結びつけ、ヘッド・媒体間の磁気的相互作用を考慮した三次元磁気記録シミュレータを実現する手法について述べるとともに、本シミュレータの収束性と計算精度についての検証を行い、超高面密度垂直磁気記録装置の設計に有効であることを証明している。

第3章では、2章で提案したシミュレータを用いて、垂直磁気記録媒体の保磁力に適応した記録ヘッド磁界強度分布と磁界勾配分布が存在することを示している。これは、実用的な垂直磁気ヘッド設計にとって重要な成果である。

第4章では、2章で提案したシミュレータの開発によってはじめて可能となった媒体内記録磁化のダウントラック方向とクロストラック方向の記録分解能に関するシミュレーションを、記録ヘッドの磁界強度分布と磁界勾配分布とを関連付けて解析し、高保磁力垂直磁気記録媒体に超高面密度記録を実現するための具体的な記録ヘッド・媒体設計指針を提示している。

第5章では、本シミュレーション手法による垂直磁気記録の再生過程シミュレーションを行い、ヘッド・媒体間の磁気的相互作用を考慮すると、狭トラック化によるダウントラック方向の再生分解能の劣化は極めて小さいことを明らかにしている。

第6章では、垂直磁気記録方式による200Gb/in^{2}程度の高面密度ハードディスク装置を実現するために必要な物理的寸法を基に、これを実現し得る垂直磁気ディスク媒体の磁気特性を本シミュレーション手法により明らかにしている。これによって垂直磁気ディスク媒体開発のための指針を明確にすることができた。

第7章は結論である。

以上要するに本論文は、ヘッド・媒体間の磁気的相互作用を考慮した精緻な三次元磁気記録再生過程シミュレーション手法の研究によって、超高面密度垂直磁気記録装置のヘッド・媒体デバイス設計を効率的に行うシミュレータを提供したものであり、情報ストレージシステム科学及びシステム情報科学の発展に寄与するところが少なくない。

よって、本論文は博士（情報科学）の学位論文として合格と認める。